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Spatial and temporal corroboration of a fire-scar-based fire history in a frequently burned ponderosa pine forest

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Abstract. Fire scars are used widely to reconstruct historical fire regime parameters in forests around the world. Because fire scars provide incomplete records of past fire occurrence at discrete points in space, inferences must be made to reconstruct fire frequency and extent across landscapes using spatial networks of fire-scar samples. Assessing the relative accuracy of fire-scar fire history reconstructions has been hampered due to a lack of empirical comparisons with independent fire history data sources. We carried out such a comparison in a 2780-ha ponderosa pine forest on Mica Mountain in southern Arizona (USA) for the time period 1937–2000. Using documentary records of fire perimeter maps and ignition locations, we compared reconstructions of key spatial and temporal fire regime parameters developed from documentary fire maps and independently collected fire-scar data ($n = 60$ plots). We found that fire-scar data provided spatially representative and complete inventories of all major fire years (>100 ha) in the study area but failed to detect most small fires. There was a strong linear relationship between the percentage of samples recording fire scars in a given year (i.e., fire-scar synchrony) and total area burned for that year ($y = 0.0003x + 0.0087$, $r^2 = 0.96$). There was also strong spatial coherence between cumulative fire frequency maps interpolated from fire-scar data and ground-mapped fire perimeters. Widely reported fire frequency summary statistics varied little between fire history data sets: fire-scar natural fire rotations (NFR) differed by <3 yr from documentary records (29.6 yr); mean fire return intervals (MFI) for large-fire years (i.e., ≥25% of study area burned) were identical between data sets (25.5 yr); fire-scar MFIs for all fire years differed by 1.2 yr from documentary records. The known seasonal timing of past fires based on documentary records was furthermore reconstructed accurately by observing intra-annual ring position of fire scars and using knowledge of tree-ring growth phenology in the Southwest. Our results demonstrate clearly that representative landscape-scale fire histories can be reconstructed accurately from spatially distributed fire-scar samples.

Key words: empirical corroboration; fire history; fire-scar data; landscape scale; National Park Service Fire Atlas maps; ponderosa pine; Saguaro National Park, southern Arizona, USA; Thiessen polygons.

Introduction

Reliable information about historical fire regimes is required to understand the long-term effects of fire and climate on ecosystem dynamics and to help guide fire and forest restoration planning (Agee 1993, Swetnam et al. 1999, Swetnam and Anderson 2008). High-resolution fire mapping and documentation is being obtained for current fires using remote sensing technology (e.g., Key and Benson 2002, Miller and Thode 2007), but key parameters of historical fire regimes, such as fire frequency, size, seasonality, and spatial patterning, must be reconstructed from limited proxy evidence left behind by past fires (Baisan and Swetnam 1990, Swetnam et al. 1999). Fire scars are the primary source of physical evidence used to date past fires and estimate fire frequency in ponderosa pine and mixed conifer forests of the western United States over the past several centuries (e.g., Baisan and Swetnam 1990, Swetnam and Baisan 1996*a*, Taylor and Skinner 1998, 2003, Everett et al. 2000, Brown et al. 2001, Heyerdahl et al. 2001, Fulé et al. 2003, Stephens et al. 2003, Veblen 2003, Brown and Wu 2005, Collins and Stephens 2007, Sherriff and Veblen 2007, Iniguez et al. 2008).

The presence of a fire scar provides irrefutable evidence of past burning at a single point in time and space (a tree bole), but interpretation of the absence of a fire scar is ambiguous because not all fires form scars on trees, not all scars persist through time, and not all trees may have burned (Dieterich and Swetnam 1984, Swetnam and Baisan 1996*a*). Fire-scar data thus provide only a partial record of past fires at discrete points on the landscape. Any broader understanding of the extent and timing of past burning between sampled points

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requires inferences about fire spread based on the spatial and temporal synchrony of fire-scar years across a network of sampled points. Empirical studies are needed to test key assumptions and interpretations used in fire-scar fire history reconstructions and to better understand the accuracy and uncertainty associated with reconstructed fire regimes (Baker and Ehle 2001, 2003, Fulé et al. 2003, Van Horne and Fulé 2006, Collins and Stephens 2007, Shapiro-Miller et al. 2007).

Fire historians have debated about the best ways to collect and interpret fire-scar data to represent historical fire patterns on landscapes (Johnson and Gutsell 1994, Swetnam and Baisan 1996*a*, Minnich et al. 2000, Baker and Ehle 2001, 2003, Fulé et al. 2003, Stephens et al. 2003, Van Horne and Fulé 2006). Beyond issues of potential bias related to sampling strategies (e.g., "targeted" vs. systematic or random sampling), much of the uncertainty in fire history reconstructions is due to a lack of systematic corroboration of fire-scar data with independently derived fire histories (e.g., mapped fires in documentary or digital forms). We use the term "corroboration" here in the sense of an empirical comparison of two independent estimates of fire history. Like fire-scar data, documentary data are also subject to various types of imprecision and inaccuracy, requiring certain assumptions and interpretations (Morgan et al. 2001, Rollins et al. 2001). Hence, we consider comparisons between fire-scar data and documentary fire maps to be a form of corroboration, achieved by comparison of two independent estimates, rather than a "validation," which might erroneously imply that one of the data types is the complete or absolute "truth" (see Turner et al. 2001:58).

Spatially explicit corroboration of fire-scar data using independent, documentary fire history is a major challenge, because it requires the co-occurrence of two relatively rare criteria. A landscape first must have enough modern fires to provide an adequate sample size (i.e., number and spatial extent of fire events) and serve as a reasonable analog to past fire regime conditions (overlapping fires). A landscape secondly must have accurately mapped documentary records derived from direct observation (e.g., dates of occurrence, causes, locations and perimeters, and other data). In the United States, contemporary documentary records are relatively complete during the past two to three decades, but few ponderosa pine forests have burned multiple times (Fulé et al. 2003). In Mexico, some pine-dominated forests have burned frequently during the 20th century, as shown by fire-scar data (e.g., Baisan and Swetnam 1995, Heyerdahl and Alvarado 2003, Stephens et al. 2003, Fulé et al. 2005), but independently mapped fire records with annual resolution are generally lacking. Consequently, corroboration of fire-scar reconstructions of past timing, frequency, and extent of fires have been largely anecdotal, limited typically to one or a small number of fire events. In the most comprehensive spatially explicit corroboration published to date, Collins and Stephens (2007) found that convex hulls drawn around opportunistically sampled fire-scar locations underestimated fire extent and total area burned statistics of overlapping 20th century fires in Yosemite (n = 5 fires) and Sequoia National Parks (n = 4 fires). In a similar analysis, Shapiro-Miller et al. (2007) reported that the relative accuracy of convex hulls from systematically sampled fire-scar locations varied depending on the source (e.g., fire atlas or remote sensing) and resultant quality and resolution of the documentary fire maps used. Fulé et al. (2003) found that fire-scar data detected all large 20th century documentary fires >8 ha in a northern Arizona ponderosa pine forest and showed good agreement between inferred timing from intra-annual ring position of fire scars and the known dates of fires. To the best of our knowledge, no published study to date has simultaneously compared multiple spatially explicit fire frequency summary statistics, or tested the accuracy of widely used analytical assumptions for reconstructing landscape-scale fire histories from fire scars.

A landscape with a contemporary fire regime suitable for comprehensive, spatially explicit fire-scar corroboration with documentary records is the Rincon Mountains of southern Arizona (Fig. 1). The ponderosa pine-dominated forests on Mica Mountain in Saguaro National Park (the larger of two major peaks in the Rincon Mountains) have experienced an unusually high frequency of 20th century fires relative to similar forests elsewhere in the United States. Based on 20th century fire maps maintained by the National Park Service (NPS), stands on Mica Mountain have burned at least nine times between 1937 and 2000. Numerous multiple-burn polygons have been mapped, and the high spatial and temporal heterogeneity of the documentary fire record provide a variety of fire frequency and extent comparisons with the tree-ring reconstructed fire history. The forests in this designated wilderness area have never been logged commercially or developed, with the exception of a primitive road (now grown over) and two log cabins (ranger stations) constructed at the summit in the early 1900s (Baisan and Swetnam 1990). This combination of extensive tree-ring records, documentary fire records, and a frequently burned landscape provides a rare opportunity to corroborate fire-scar fire history reconstructions against independently derived documentary fire maps.

The primary purpose of our research was to test basic assumptions and analytical approaches used by fire historians to reconstruct landscape-scale fire histories from point-based fire scars. We compared spatial and temporal fire history parameters derived independently from fire-scar data and NPS fire maps to accomplish this goal. We additionally addressed long-standing uncertainties about inferring fire spatial patterns and geographic extents from distributed plots. For this research we assumed that ground-mapped fire perimeters within the study area provided sufficiently complete and

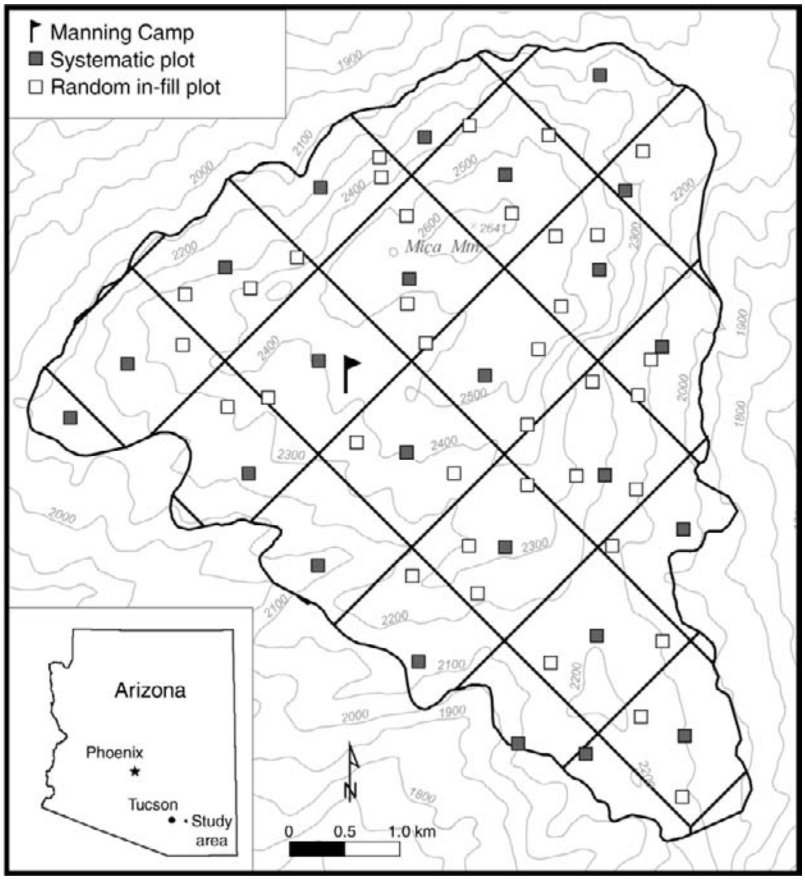

FIG. 1. Location of the Mica Mountain study area and fire-scar plots in Saguaro National Park, southern Arizona.

accurate data to corroborate fire histories reconstructed from fire scars (for reasons we discuss in more detail in the following sections).

We sought answers to the following research questions: How effective are fire-scar data at providing a complete inventory of fire years recorded in the documentary data? What is the relationship between fire-scar synchrony and annual area burned? How similar/dissimilar are the reconstructed quantities of burned areas estimated from fire scars and ground-mapped burned areas? How similar/dissimilar are spatially explicit fire frequency maps interpolated from fire scars and documentary perimeter maps? How much do fire frequency summary statistics differ between fire-scar and documentary data and between different methods of calculation? How accurately do intra-annual positions of fire scars represent the timing of past fires as known from documentary records? These questions are designed to address broader issues of spatial and temporal uncertainty associated with the interpretation of point data.

TWENTIETH CENTURY DOCUMENTARY FIRE RECORDS

The National Park Service (NPS) has maintained detailed records and maps of fires on Mica Mountain since 1937. The intent was to map as many fires as possible and record information about fire size, cause, origin date, and control actions. Older fires <30 ha in size were generally mapped as points (at their origin), but most fires >30 ha were mapped as perimeter polygons. These fire records were maintained in a database updated annually, referred to hereafter as the "NPS Fire Atlas" (Swantek 1999*a*, *b*, Saguaro National Park 2002). Several large fires prior to the 1990s were ground-mapped by government survey crews or by fire crews immediately after burning. More recent fires were mapped using Global Positioning System (GPS) technology and satellite remote sensing (Henry and Yool 2002). A valuable feature of the NPS Fire Atlas for our analyses was the abundance of overlapping burn polygons (fire perimeters), representing areas that have burned at different frequencies, from once to as many as nine times between 1937 and 2000.

Although the NPS intended to document all fires that occurred in the Rincon Mountains, it is quite likely that some small lightning-ignited fires, common during the Arizona "monsoon" season (i.e., early July through August), were not recorded. Such small fires were often extinguished by rain before being detected or were not managed or mapped. Another limitation of the NPS

Fire Atlas was that no unburned areas (or severity levels) were mapped within individual fire perimeters (polygons) for most burns. It is known from experience in these forest types that some areas enclosed within mapped perimeters generally remain unburned. The positional accuracy of some small fires mapped as points prior to GPS technology are unknown, but considerable effort was made by NPS personnel to describe in detail the locations of even small fires. All large fire perimeters are considered reasonably accurate (the largest of which were surveyed), but it is quite likely that there are some mapping errors in the database.

The NPS Fire Atlas documented 414 fires within the study area between 1937 and 2000, for an average of 6.5 fires/yr (Table 1). Multiple fires occurred every year. Total area burned by all fires during the 64-yr period was 6636 ha. Most years had only small fires that burned <40 cumulative hectares. There were, however, 21 large fires that burned >100 ha (and up to ~1600 ha) distributed across 12 different fire years. These 12 years accounted for 19% of the 64 fire years during the study period, and 97% of the 6636 ha burned. The overlapping fire perimeters formed multiple-burn polygons consisting of many combinations of individual fire years and extents across the landscape. Lightning-ignited fires accounted for 93% of all fires and 86% of the total area burned during the study period, consistent with the findings of Baisan and Swetnam (1990). There were six management-ignited prescribed burns that comprised most of the remaining 14% of the burned area. Human-caused wildfires accounted for 6% of all fires, but <1% of the total burned area.

Table 1. Summary of documentary fire occurrence records for the 2780-ha Mica Mountain study area (Saguaro National Park, southern Arizona) from 1937 to 2000, based on the National Park Service Fire Atlas (Saguaro National Park 2002).

Fire type	No. fire years	No. individual fires	Area burned (ha)	No. mapped fire perimeters
Lightning		383	5697	16
Human		25	10	
Prescribed burns		6	929	5
Total	64	414	6636	21

Methods

Study area description

The study area is located in the Rincon Mountains in Saguaro National Park Wilderness Area just east of Tucson, Arizona, USA (Fig. 1). The Rincon Mountains are a Sonoran Desert "sky island," rising from the desert floor at an elevation of 940 m to the forested summit of Mica Mountain at 2641 m. The mountain harbors extensive coniferous forests at the high elevations (Bowers and McLaughlin 1987). The study area polygon is 2780 ha and traces the extent of the coniferous forest belt on Mica Mountain. The polygon was delineated prior to field sampling, using aerial photography to map the lower forest ecotone. Ponderosa pine (*Pinus ponderosa* P.& C. Lawson) or Arizona pine (*Pinus ponderosa* var. *arizonica*) is the dominant tree species above 2100 m. Southwestern white pine (*Pinus strobiformis* Engelm.) is a ubiquitous codominant above 2300 m. Gambel oak (*Quercus gambelii* Nutt.) occurs as isolated individuals or in small clusters on cooler aspects throughout this zone. White fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr) and Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) form small, isolated mixed-conifer stands with ponderosa and Southwestern white pine on some north aspects in the northern part of the study area. Ponderosa pine decreases in dominance at lower elevations and becomes locally absent near the lower study area boundary. Alligator juniper (*Juniperus deppeana* Steud.), border pinyon (*Pinus discolor* D. K. Bailey & Hawksworth), Arizona white oak (*Quercus arizonica* Sarg.), and silverleaf oak (*Quercus hypoleucoides* A. Camus) are common at the lower elevations near the lower forest ecotone (below 2200 m).

Average annual precipitation varies strongly with elevation, ranging from ~33 cm at the base of Mica Mountain (800 m elevation) to ~89 cm near the summit at Manning Camp (2438 m elevation). The seasonal distribution of precipitation is bimodal. About 58% falls as rain between May and September and peaks in July and August during the wet summer monsoon season. The remainder falls as rain or snow between October and March and peaks in December and January. Fire season typically occurs between April and September. Maximum area burned peaks during June, whereas the maximum number of ignitions is in early July, coincident with the monsoon and peak lightning occurrence season (Baisan and Swetnam 1990, Crimmins and Comrie 2004). Most 20th century fires were ignited by lightning (Table 1 and Baisan and Swetnam 1990). Lightning fires are common during the monsoon season in July and August, but rarely become widespread before being extinguished by rain.

Fires on Mica Mountain were managed by the U.S. Forest Service from 1906 to 1933 and by the National Park Service from 1933 to the present. Rugged terrain and poor access in the study area enabled many spring and arid foresummer fires to grow relatively large (>200 ha) before being suppressed. A prescribed natural fire program (termed "wildland fire for resource benefit" today) was implemented briefly between 1972 and 1994 to allow some lightning ignitions in the wilderness to burn under certain conditions. Three lightning fires during this period were allowed to grow to >200 ha before eventually being suppressed.

Fire-scar data

We sampled fire scars from 60 1-ha plots using a two-phase systematic and random sampling approach. The purpose was to provide a uniform distribution of sample plots with variable densities completely independent of the fire atlas. An initial plot was established randomly within the study area. From this plot, a 1.2-km grid was generated with a 45° orientation to maximize the number of grid cells within the study area. Twenty-four plots were systematically generated during the first phase within the center of each 1.2-km grid (Fig. 1). Thirty-six additional plots were located randomly between initial grid points during the second phase to increase the sampling density and create greater variation in lag distances between points. When plots were located on rock outcrops or barren ground, they were moved to the nearest forest stand. Some low-elevation grid cells had a lower plot density because forest cover was sparse near the ecotone.

Within each plot we collected 3–14 fire-scarred cross sections from living trees and remnant wood (i.e., logs, stumps, snags). Of the 405 fire-scarred cross sections sampled, 202 encompassed part or all of the corroboration period (1937–2000) and 203 were remnant specimens. In many cases we collected all of the fire-scarred material that was present within each 1-ha plot. Where there was an abundance of material, we sampled trees with well-preserved fire scars that provided a combination of records from both young and old specimens to maximize the length and completeness of the temporal record. All cross sections were prepared and cross-dated in the laboratory using standard dendrochronology techniques (Stokes and Smiley 1968). All fire scars were assigned a calendar year, and where possible, an intra-annual ring position to determine the approximate seasonal timing of fires (Dieterich and Swetnam 1984, Baisan and Swetnam 1990).

Because trees may not record (or preserve) all fires that burned the bole, all fire-scar years within individual plots were combined to form a composite master fire chronology for each plot (sensu Dieterich 1980). Vegetation and topography were typically homogeneous within the plots, so the composite plot chronologies are reasonably assumed to be relatively complete inventories of fire events within the 1-ha sampling areas during the time spans encompassed by the tree-ring specimens. The composite fire records from each plot were analyzed collectively as a "point," and we made no inference or assumptions about within-plot spatial or temporal heterogeneity. There were $\geq$57 plots capable of recording fires each year during the analysis period (referred to subsequently as "sample depth"); the number varied little due to the use of plot-level compositing and the recent time period of the study.

Data analysis

Fire year inventory.—A common objective of fire history research is to obtain a complete inventory of fire years within a given area, particularly "major" fire years with widespread burning (Swetnam and Baisan 1996*a*, Van Horne and Fulé 2006). We calculated (from the NPS Fire Atlas) the proportion of documented fire years in the study area detected by the fire-scar network. To assess how fire-scar detection varied as a function of area burned, we used three different sets of documented fire events: all fire years, years with at least 40 ha burned, and years with at least 100 ha burned.

We constructed a 2 $\times$ 2 error matrix to quantify potential ranges of fire-scar detection error based on the error typology described in Falk (2004). In this case, Type I error occurs when a fire-scar plot within a mapped fire perimeter fails to detect that corresponding fire, and Type II error occurs when a fire-scar year is detected within a plot where there is no documentary fire year shown. Only "extensive fires," which we define here as a mapped fire perimeter large enough to encompass at least two fire-scar plots, were evaluated in the analyses. This is because small "spot" fires were mapped as discrete points with varying spatial accuracy over time, and it would be impossible to determine with any certainty whether plots and mapped spot fires actually intersected at that scale. The failure of fire-scar data to "detect" small fires between sample locations moreover would be due to sampling resolution rather than Type I error.

Combining fire-scar years from multiple samples within a specified area, or a composite fire chronology (sensu Dieterich 1980), is assumed to result in a more complete inventory of fire events, because not all samples record (or preserve) all fire years. To assess the relative importance of compositing on the detection of extensive fires that burned through each plot, we calculated the proportion of extensive fire-scar years in each plot that required compositing to detect.

Percent scarring and area burned.—Annual fire-scar synchrony, or the proportion of sample units (i.e., plots in our study) that record a fire in a given year, has been used widely by fire historians as a relative index of total area burned (e.g., Morrison and Swanson 1990, Swetnam 1993, Taylor and Skinner 1998). We tested this assumption by regressing the percentage of plots scarred annually against the corresponding area burned (in hectares) documented independently by the NPS Fire Atlas data. In many fire-scar studies, percent scarring of samples has been sorted, or filtered, into categories based on a specified percentage scarring threshold. This is intended to eliminate the influence of smaller fires that scar only small numbers of trees. Although any threshold percentage can be used, filtering at the $\geq$10% and $\geq$25% level has been reported most widely in the fire history literature to represent larger burns. To assess the validity of this approach for representing relative area burned, we compared the average annual burned area (ha) for fire years in which $\geq$10% and $\geq$25% of the plots recorded a scar with the average for all fire years.

Spatial pattern interpolation.—We used Thiessen polygon tessellations, known also as Voronoi diagrams (Burrough and McDonnel 1998), to interpolate fire-scar data into spatially explicit fire perimeter maps. Based on spatial autocorrelation inherent in most spatial data sets, the Thiessen polygon approach rests on the simple assumption that the presence/absence of a fire event at an unsampled location is predicted best by the presence/absence of a fire event at the nearest data point reference. The Thiessen approach was selected for our study for three reasons: First, Thiessen polygon tessellations closely resemble qualitative, expert knowledge-based techniques used commonly by fire historians, whereby perimeters are drawn between scarred and unscarred plots. Second, this approach required the least amount of parameterization and subjective user input, which was important in this study to prevent bias because the fire locations were already known. Third, this approach is well suited for interpolating binary data (such as fire maps) from broadly distributed data points.

Two rules were used to determine which fire-scarred plots were interpolated and how exact fire boundaries were determined: (1) at least two adjacent plots had to be scarred in a given year for a fire to be interpolated, and (2) if a polygon lacking a fire scar in a given year at a centroid plot was 100% surrounded by burned polygons in that year, it was recorded as burned. The first rule was conservative and assumed that fire-scar years restricted to single plots or widely separated plots did not burn beyond the plot boundary (or boundaries). The second rule assumed, conversely, that when a single unscarred plot was completely surrounded by scarred plots, fire burned throughout a significant proportion of the polygon, as in the adjacent polygons. It is likely that unburned areas sometimes occurred within larger burned areas, but the second rule is consistent with assumptions associated with the NPS Fire Atlas maps (i.e., all areas within NPS mapped polygons were assumed to have burned). Both assumptions were consistent with the overall goal of mapping external perimeters of fires and total areas encompassed, rather than internal heterogeneity (burned and unburned subareas) of polygons.

Individual fire perimeters interpolated from fire-scar plots were combined to create a single, spatially explicit fire frequency map for the study area. A similar fire frequency map was created from the NPS Fire Atlas data and compared with the fire-scar-based map. Pearson's cross-correlation coefficient (Zar 1999) was calculated between the two maps to compare the correspondence of fire frequency values (30-m grain). The proportion of the study area occupied by each fire frequency class was compared between fire-scar data (predicted) and NPS Fire Atlas data (expected) using a two-sample Kolmogorov-Smirnov Test ($\alpha = 0.05$) (Zar 1999).

Annual area burned.—Annual area burned is an important fire regime parameter and is used to calculate fire frequency statistics such as the natural fire rotation (NFR) (Agee 1993). Area burned can be estimated using a spatially explicit interpolation procedure such as Thiessen polygons or a spatially implicit procedure such as the relationship between fire size and fire-scar synchrony. The former uses the spatial coherence of scarred plots and the latter assumes each actively recording sample unit represents some fixed proportion of the landscape. We estimated annual area burned from fire-scar data using examples of both approaches: (1) we calculated the area of interpolated Thiessen polygon fire perimeters described previously, and (2) we assumed that the annual percentage of distributed plots scarred in a given year (fire-scar synchrony) was equivalent to the percentage of the study area burned (i.e., 1:1 ratio). We plotted fire-scar estimates of annual area burned against documentary area burned extracted from the NPS Fire Atlas to assess the relative accuracy of each approach.

Fire frequency summary statistics.—The two summary statistics reported most widely in the literature to summarize the fire frequency–area distribution are the composite mean fire return interval (MFI) and the NFR. The composite MFI is the average number of years between fires of any size that occurred within a specified area (Romme 1980). Note that unless otherwise stated, all detected fire years are included in the calculation of the composite MFI regardless of their size. This is because compositing was intended to be used in relatively small or homogenous areas where fire spread is assumed, and/or where any fire is determined to be of significance or interest (Dieterich 1980). It has become customary, therefore, to add a "relative area burned" component to the MFI to determine the mean interval between larger fire years. This is done by calculating mean intervals only for fire years that scar a minimum percentage of samples, which has the effect of filtering out intervals between presumably smaller and isolated fire years (Swetnam and Baisan 1996*a*, *b*). Filtering at the 10% and 25% level is most common, meaning that only intervals of fire years recorded by $\geq$10% or $\geq$25% of recording samples, respectively, are used in the calculation. We denote the level of filtering hereafter with a subscript (e.g., $MFI_{10\%}$, $MFI_{25\%}$, or MFI_{all} for "all fire years").

The NFR is defined as the average number of years required for an area *equivalent* to the study area to burn (e.g., 2780 ha for the Mica Mountain study area) (Romme 1980, Agee 1993). The value of the NFR is theoretically analogous to the Fire Cycle (Agee 1993), which is estimated from stand age distributions, and the population mean fire interval (sensu Baker and Ehle 2001). The NFR is based on cumulative area burned for a specified time period rather than the frequency of fire years.

We compared the fire-scar MFI_{all}, $MFI_{10\%}$, and $MFI_{25\%}$ with the corresponding NPS Fire Atlas values for the study area. Only scar-to-scar intervals were included for fire-scar calculations because of ambiguity of the period before the first scar (see Van Horne and Fulé 2006). The unfiltered MFI_{all} was directly comparable between fire scars and maps because it is based solely on the presence or absence of any fire year. Filtered MFI values were not directly comparable

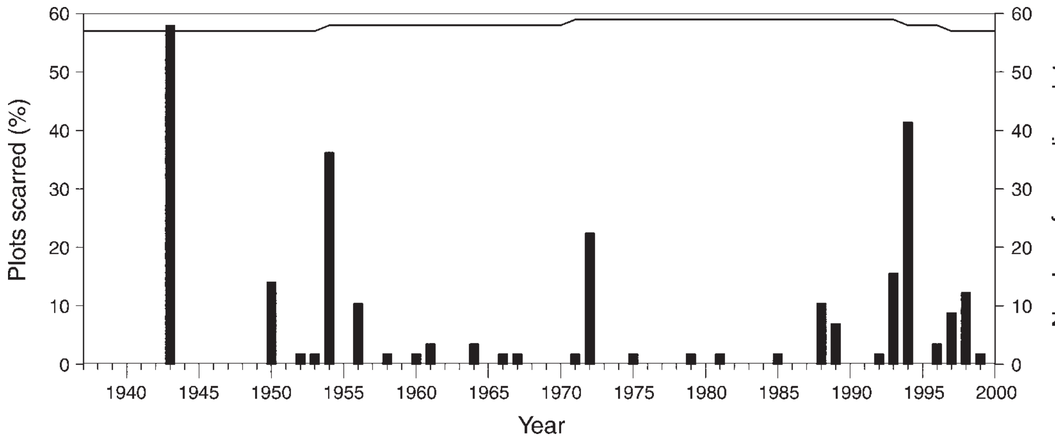

FIG. 2. The percentage of fire-scar plots that recorded a fire year (solid bars) and the total number of recording plots (solid line at top of graph) between 1937 and 2000.

between data sets because fire-scar data consisted of points, whereas fire atlas maps consisted of area polygons. It was necessary, therefore, to convert point-based fire-scar data to area-based perimeter maps for a standardized comparison. For Fire Atlas maps, we calculated filtered MFI values for fire years in which $\geq$10% and $\geq$25% of the study area burned. For fire-scar data, we calculated both a point-filtered MFI from fire years in which $\geq$10% and $\geq$25% of the plots burned, and an area-based filtered MFI from fire years in which $\geq$10% and $\geq$25% of the study area burned as determined from fire-scar interpolated perimeter maps.

We calculated the study area NFR for each data set using the following equation:

$$\mathrm{NFR} = T/P \quad (1)$$

where T was the number of years (1937 to 2000 in this case) and P was the cumulative proportion of the study area burned (which can be >100%). We calculated P for NPS Fire Atlas data by directly extracting area burned from GIS fire maps. We calculated P for fire-scar data using area burned estimated from both Thiessen polygons fire-scar synchrony ratios. All fire years were used for the latter approach, even if they were recorded at only one plot.

Fire seasonality.—The relative intra-annual ring position of fire scars can be used to estimate the approximate seasonal timing of burning (e.g., Dieterich and Swetnam 1984, Baisan and Swetnam 1990, Fulé et el. 2003). The beginning and end date of each large fire was recorded in the NPS Fire Atlas, so that we were able to compare the predicted month of occurrence from fire scars with an actual documented month of fire occurrence. We constructed percent frequency histograms for the six fires with the largest number of clear, seasonally dated fire scars to determine if the observed modal ring position corresponded with the expected ring position based on known fire dates and the known tree growth phenology (i.e., timing of cambial growth initiation, rate, and cessation), for conifers in the Southwest (Fritts 1976, Baisan and Swetnam 1994; C. Allen, *unpublished data*).

RESULTS

Fire year inventory

Twenty-seven fire years were detected by fire scars in the study area between 1937 and 2000, of which 14 were detected at multiple plots (range 2–35 plots), and 13 years were detected at only a single plot (Fig. 2). The probability of a documented fire year being detected by fire scars increased strongly with increasing area burned: 43% of the 64 documentary fire years were detected by fire scars overall, but 100% of the 12 fire years with >100 ha burned were detected by multiple plots (Table 2). Fire scars thus provided a complete inventory of all large fire years that resulted in >97% of the total area burned.

The number of actively recording fire-scar plots within each of the 21 mapped fire perimeters ranged from 1 to 39, for a cumulative total of 159 possible detections. Fire scars recorded the corresponding

TABLE 2. Number of fire years documented in the National Park Service Fire Atlas that were detected by fire-scar plots.

Annual area burned filter	Documentary fire years	Detected by fire scars	
		At least one plot	At least two plots
All fire years	64	27 (42%)	14 (22%)
Fires years with $\geq$40 ha burned	16	13 (81%)	12 (75%)
Fires years with $\geq$100 ha burned	12	12 (100%)	12 (100%)

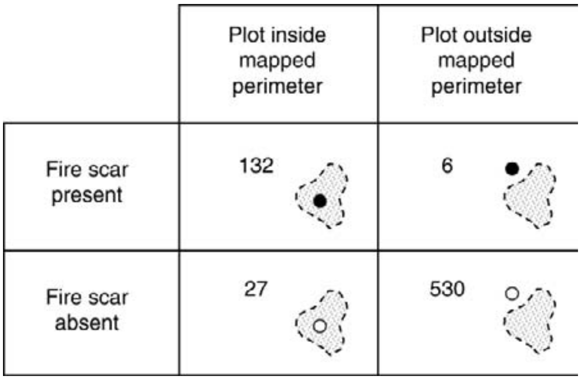

FIG. 3. Error matrix showing the number of plots within mapped fire perimeters that recorded a fire-scar year. The conceptual diagrams graphically depict all four possible outcomes. Shaded areas within dashed lines represent a mapped fire perimeter, open circles represent a fire history plot that did not record a fire, and solid circles represent fire history plots that recorded a fire. Overall agreement = 95% (662 correct outcomes out of 695). Type II error: 17% (fire scar is absent within a mapped perimeter). Type I error: 1% (fire scar is present outside a mapped perimeter).

mapped fire 132 (83%) times, with a corresponding Type II error of 17% (Fig. 3). This is a maximum (liberal) estimate fire-scar Type II error, because in some cases a plot within a perimeter actually may not have burned. There were 6 cases out of a possible 600 in which a plot recorded an extensive fire, even though it was located outside of the mapped perimeter. Although this technically constitutes a Type I error of 1%, all six detections were located <100 m from the corresponding fire perimeter with the same date, so a false fire-scar detection or tree-ring dating error is unlikely in these cases, and it is more likely that the mapped perimeter was in error.

Compositing the fire-scar years from multiple trees was necessary to ensure a complete record of extensive fires that burned through individual plots, especially in plots that experienced high fire frequency (Table 3). In the 31 plots that recorded only 2–3 extensive NPS Fire Atlas fires, compositing was required to detect all years in 16% (5) of the cases (i.e., a single tree contained all fire years 84% of the time). However, in the 11 fire-scar plots that recorded >4 extensive fires, compositing was required to detect all extensive fire years in 55% (6) of the cases (i.e., a single tree contained all fire years only 45% of the time).

Fire-scar synchrony

There was a strong linear relationship between the percentage of fire-scar plots recording a fire year (fire-scar synchrony) and the amount of area burned ($r^2 = 0.96$; $y = 0.0003x + 0.0087$) (Fig. 4A). Synchronous scarring of >2 plots in a given year resulted exclusively from one or more extensive fires that spread between plots; in no case did the simultaneous co-occurrence of small fires result in scars at more than two plots during

TABLE 3. Proportion of plots where compositing was required to identify all extensive fire years within a plot.

Number of extensive fire-scar years in a plot	Number of plots	Compositing required
2–3	31	5 (16%)
≥4	11	6 (55%)

Note: Extensive fires are defined as fires large enough to have spread across multiple plots.

the same year. In only two years, 1961 and 1964, did two plots record fires known not to have spread between them (based on the NPS Fire Atlas data), and only in 1964 were the plots adjacent to each other.

Spatial patterns of fire frequency

There was strong agreement of fire frequency spatial patterns between interpolated fire-scar maps and the NPS Fire Atlas (Figs. 5 and 6). Pearson's cross correlation between data sets was $r = 0.81$ ($P = 0.001$), reflecting the strong graphical correspondence between

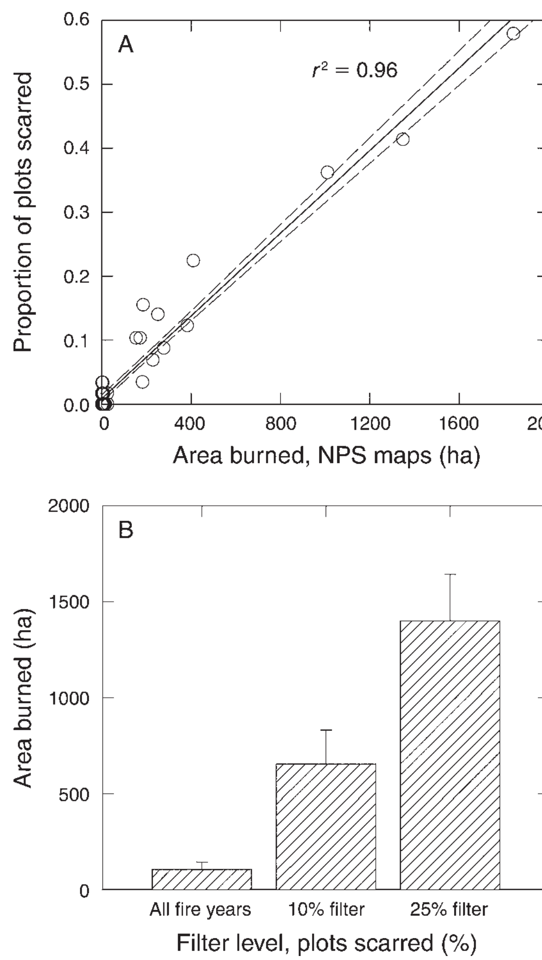

FIG. 4. Relationship between (A) annual area burned and fire-scar synchrony ($y = 0.0003x + 0.0087$, $r^2 = 0.96$, $P \ll 0.001$), and between (B) mean annual area burned and three categorical levels of fire-scar filtering. Error bars represent +SE.

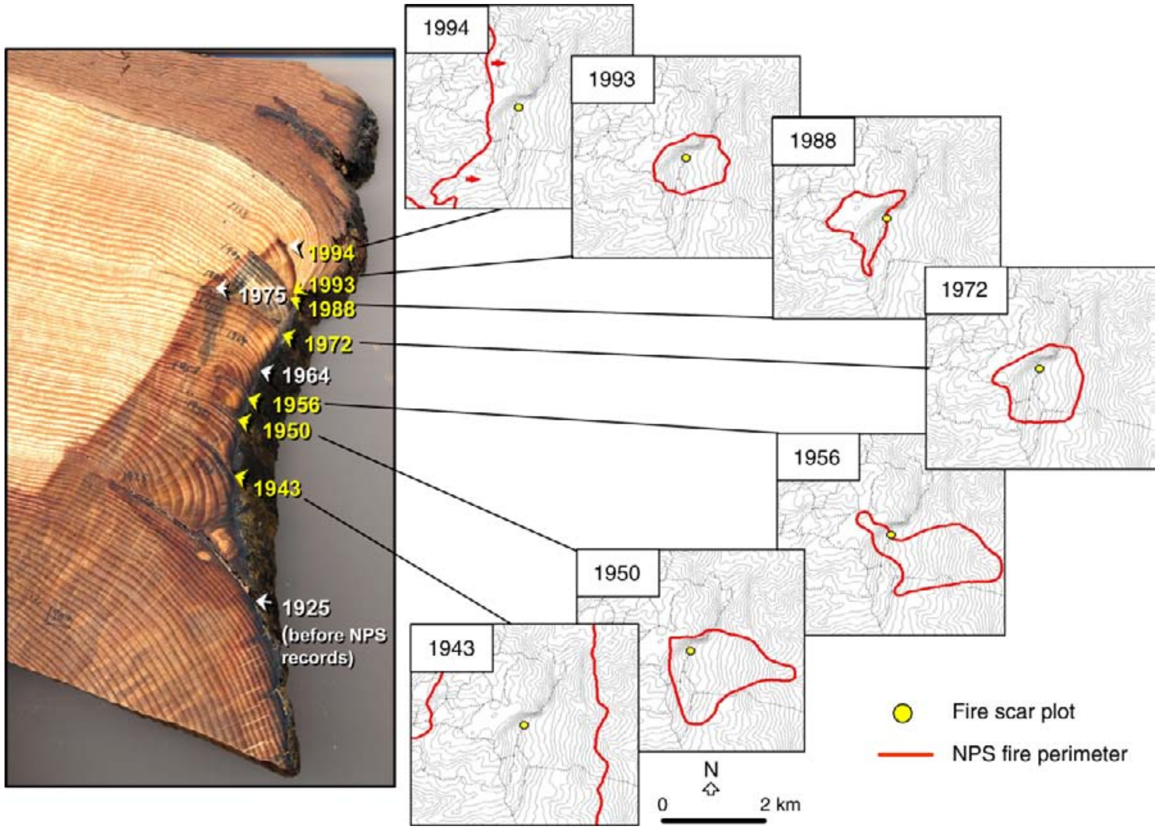

FIG. 5. Partial cross-section of ponderosa pine from Mica Mountain showing corresponding fire maps for each fire-scar year. Fire years shown in yellow indicate extensive fires that burned multiple adjacent plots. Fire years shown in white indicate small fires that did not scar adjacent plots and have no corresponding perimeter map (arrows for the 1994 map indicate the interior side of the fire polygon). Photo credit: C. A. Farris.

maps. Less than 15% of the total area in each map (fire-scar vs. NPS Fire Atlas estimated) differed by a frequency of more than one fire, and there were no consistent patterns of over- or underestimation that would indicate a strong bias in the fire-scar data or NPS mapped data (Fig. 6C). The biggest difference between the predicted and mapped area of any fire frequency class was <5%, and overall differences between classes were not statistically significant ($P = 0.97$).

Area burned estimation

Estimation of annual area burned from fire scars correlated closely with area burned derived from ground-mapped fire perimeters: $r^2 = 0.97$, $y = 0.819x + 35.5$, for Thiessen polygons; $r^2 = 0.96$, $y = 0.898x + 24.1$, for fire-scar synchrony ratio (Fig. 7). As expected with a broadly distributed sampling distribution, the Thiessen polygon and fire-scar ratio methods were very similar and resulted in regression slopes approaching a 1:1 relationship with the reference data. Given the broad spatial distribution of sample data in this study, spatially explicit interpolation and relativistic extrapolation methods both provided excellent estimates of area burned.

Fire frequency summary statistics

The fire-scar MFI_{all} for the study area was 2.2 yr compared to 1.0 yr for the NPS Fire Atlas (Table 4). Although not all fire years were detected by the fire-scar network, the difference in the MFI was small because the value asymptotically approaches 1.0 for large landscapes of this size (Falk and Swetnam 2003, Falk 2004), which is considerably larger than what unfiltered compositing was intended for. Filtered fire-scar MFI values corresponded very closely with the fire atlas values regardless of whether area or point-based filtering was used (Table 4). The fire-scar and NPS Fire Atlas $MFI_{25\%}$ were identical (25.5 yr) because they incorporated the exact same fire years (Table 4). The NPS Fire Atlas $MFI_{10\%}$ was 11 yr compared to 9.2 yr for comparable area-based fire-scar data. The point filtered fire-scar $MFI_{10\%}$ was slightly lower at 6.9 yr because two extra fire years were counted that scarred 10.3% of the plots (points), but just slightly less than 10% of the study area.

The reference NFR calculated from NPS Fire Atlas maps was 26.8 yr and differed by <3 yr from the fire-scar NFR (Table 4). The interpolated fire-scar NFR was 29.6 yr and the fire-scar NFR estimated using fire-scar

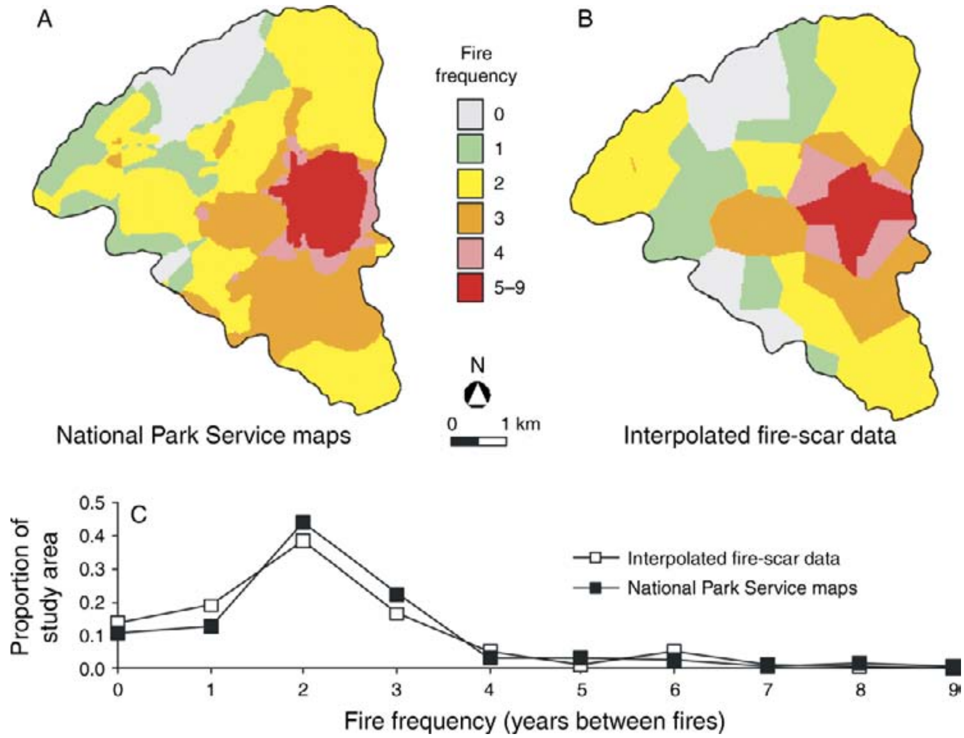

FIG. 6. Spatial patterns of fire frequency from 1937 and 2000 calculated from (A) National Park Service Fire Atlas maps and (B) fire-scar data interpolated with Thiessen polygons. (C) The proportion of the study area occupied by each fire frequency class in the two maps (panels A and B).

synchrony (percent scarring) was 23.9 yr. This value was slightly lower because, unlike Thiessen polygon interpolations, we did not filter out fire-scar years that did not scar at least two adjacent plots (this added ~600 ha of cumulative area burned).

Fire seasonality

The modal intra-annual fire-scar position matched the expected ring position according to the known seasonal occurrence of the fire in all cases (Fig. 8). Due to variation in local site conditions, tree phenology, and our ability to visually discern intra-ring scar positions on some samples, each fire exhibited a range of intra-ring positions on samples rather than just a single expected position. Two late-season fires that occurred after the monsoon (one lightning-caused and one prescribed burn) resulted in scars exactly on the ring boundary that were incorrectly assigned to the "dormant" position of the following year in a few samples. The positions of most scars those years were correctly assigned to the current year's late wood, however, so there was no dating error in terms of assigning the correct calendar year. The 1997 prescribed burn occurred in late November, which is well after large lightning fires typically occur in the region.

DISCUSSION

The results of this study demonstrate clearly that broadly distributed fire-scar data can be used to characterize accurately numerous temporal and spatial aspects of past fire occurrence in landscapes. These data provide better understanding of how fire-scar reconstructions reflect patterns of actual fire occurrence across landscapes and provide a robust framework for interpreting historical fire regimes using fire-scar data.

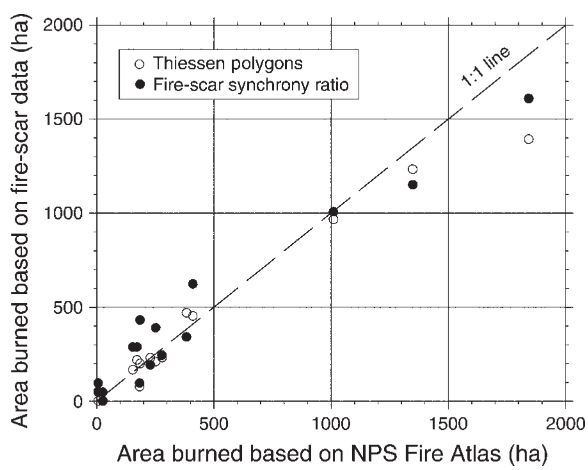

FIG. 7. Relationship between annual area burned (hectares) calculated from NPS Fire Atlas maps and reconstructed from fire-scar data. Fire-scar data were converted to hectares burned using area burned from fire-scar data: Thiessen polygons ($y = 0.819x + 35.5$, $r^2 = 0.97$, $P < 0.001$); fire-scar synchrony ratio ($y = 0.898x + 24.1$, $r^2 = 0.96$, $P < 0.001$). The diagonal dashed line represents a 1:1 relationship.

TABLE 4. Comparison of composite scar-to-scar mean fire return intervals (MFI) filtered at different levels and natural fire rotation (NFR) for the Mica Mountain study area estimated from the National Park Service Fire Atlas (Saguaro National Park 2002) and fire-scar data.

Fire frequency metric	Time period†	Area-based calculation‡		Point-based calculation§
		NPS Fire Atlas	Fire scars	Fire scars
Composite MFI				
MFI_{all}	1943–1998	1.0 (0.0)	2.2 (0.4)	2.2 (0.4)
$MFI_{10\%}$	1943–1998	11.0 (4.0)	9.2 (3.6)	6.9 (3.2)
$MFI_{25\%}$	1943–1994	25.5 (15)	25.5 (15)	25.5 (15)
Natural fire rotation (NFR)	1937–2000	26.8	29.6	23.9

Note: Values are in years (mean with SE in parentheses).

† Time period between the first and last fire scar for MFI calculations.

‡ Filtered MFIs for fire atlas data were calculated based on the percentage of area burned. Filtered fire-scar MFIs and the NFR were calculated using area-based Thiessen polygon interpolations for a standardized comparison. (Values are in years; means with standard errors in parentheses.) See *Data analysis: Spatial pattern interpolation*.

§ Filtered fire-scar MFIs and the NFR were calculated using the percentage of plots scarred.

Interpreting the fire-scar record

Reconstructing representative fire histories from fire scars requires an understanding of how fire-scar sampling networks record fire years. Large fires have a much higher probability of being detected by fire-scar networks than smaller fires that are more numerous but burn little cumulative area. This pattern was illustrated clearly on Mica Mountain, where every fire year >100 ha was detected by multiple samples, compared to only 3.8% of the fire years <100 ha. Fulé et al. (2003) found a similar pattern in Grand Canyon National Park, where fire scars provided a complete inventory only for the larger fires in the documentary fire atlas. Moreover, spatially distributed fire-scar data tend to record fire years in relative proportion to the amount of area burned. This was evident by the strong linear correlation between fire-scar synchrony and annual burned area on Mica Mountain. Estimation of fire-scar synchrony has been shown to be robust across a relatively wide range of sample size, sampling designs (e.g., opportunistic vs. probabilistic sampling), spatial scales, and geographic settings in pre-settlement Southwestern pine forests

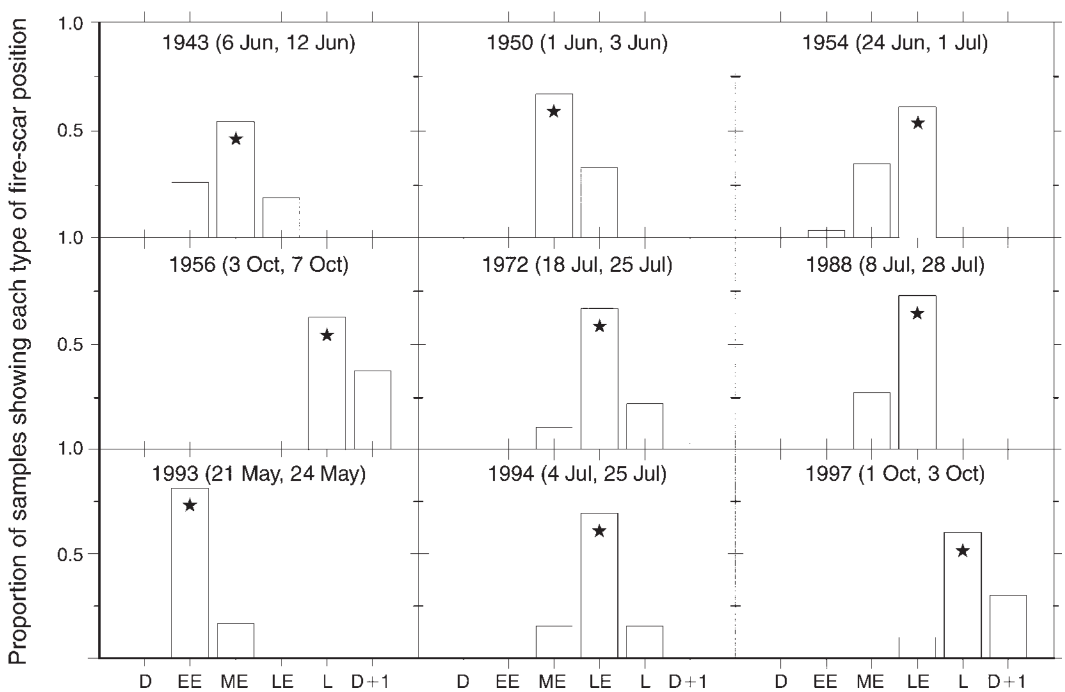

FIG. 8. Frequency distribution of the relative fire-scar position within intra-annual tree rings for nine large fire years. A star indicates the expected scar position based on the reported burn dates in the National Park Service Fire Atlas. The discovery date and control date for each fire are shown in parentheses. Seasonal occurrence abbreviations are: D, dormant (before mid-May); EE, early–early (mid-May to early June); ME, middle–early (June); LE, late–early (late June or July); L, late (early August to mid-October); and D+1, dormant scar dated to the following year.

(Van Horne and Fulé 2006, Farris 2009). The results of this study thus provide strong empirical support for two key assumptions used by fire historians to reconstruct fire frequency parameters: (1) fire-scar synchrony is an accurate proxy for annual area burned, and (2) filtering based on scarring percentage provides a meaningful relative index of major fire years by eliminating small fires. Our results also confirmed that compositing increases the likelihood of obtaining complete inventories of major fire years in sampled stands, even though individual trees are imperfect recorders. Compositing was particularly useful in areas with the highest fire frequencies and/or short-interval fire years where scar formation and retention could be quite variable (Collins and Stephens 2007).

Minnich et al. (2000) argued that the relationship between fire-scar synchrony and annual area burned is equivocal because numerous small fires may scar trees at multiple sample locations in the same year. They speculated that, in the Sierra San Pedro Mártir in northern Mexico, small "spot" fire (<5 ha) densities in mixed conifer forests may approach 1 fire/ha over a 52-yr period (the estimated NFR), which might result in multiple fire scars from small fires in the same year. A conservative estimate of "spot" fire density on Mica Mountain based on the NPS atlas would be ~1 fire/8 ha during a similar 52-yr period. The actual value is likely higher due to unmapped monsoon-season ignitions. If Minnich et al.'s (2000) point were applicable, we would expect to see numerous small fires recorded in separate sample locations, given the large sample size and high ignition and lightning density on Mica Mountain and the Southwest (Allen 2002). We instead found that synchronous scarring at more than two sites resulted exclusively from widespread fires that burned between plots (as indicated in the NPS atlas). Only twice did the same fire-scar year in separate plots result from individual small burns (1 and 5 ha, respectively), and in only one of those cases were the scarred plots adjacent to each other (it is possible also that the fire atlas map was incorrect and the fire did spread between plots). This is not an artifact of the suppression era, because multiple, nonadjacent fire scars were equally rare in this data set prior to 1900 and also with targeted samples (Baisan and Swetnam 1990). These results are consistent with Stephens et al. (2003), who found that widespread fire years scarred at the 25% filter level generally corresponded with large fire frequencies reconstructed from aerial photos during the same period in the Sierra San Pedro Mártir.

Based upon our observations and logic, we posit that there are at least five reasons why small fires at multiple sample locations in the same years are highly unlikely to result in an overestimation of large fire extent or frequency from fire-scar data. First, small fires would have to occur (and be detected) at many separate sample locations in a given year to result in a significant misclassification of area burned. In simulations with our data set (not shown) we found that this would typically involve 10–25% or more of the sample locations recording separate small fires in a given year, or 6–15 plots. The occurrence of multiple small fires at just two or three plots in the same year (assuming they are recorded) would not appreciably influence estimation of cumulative area burned or resultant area-based summary statistics, such as the NFR. Second, such high rates of small-fire synchrony at multiple plots would have to occur *repeatedly* over many years to result in any meaningful bias (i.e., only one or two years with numerous plots scarred by small fires would have relatively little influence statistically). Third, widespread fires are typically recorded by adjacent fire-scar samples and are clearly clustered spatially, making them easily distinguishable as spreading fires rather than multiple small fires. Fourth, we observed that the same groups and combinations of plots tended to record the widespread fire years repeatedly over time (and often the same, multiple-scarred trees within those plots). The probability that small, spatially discrete fires would (a) repeatedly burn in the same random/systematic plots *and* (b) form scars on the same trees, is exceedingly small. Finally, because scale dependence is very strong for small fires but decreases significantly with increasing fire size, large fires are on average disproportionately more common at fine scales where scar formation actually occurs (Falk et al. 2007, Farris 2009). This ensures that filtering of cross-dated fire-scar years will effectively discriminate between isolated small fires and large burns.

Spatial patterns of fire occurrence

There was very strong spatial agreement between fire frequency maps interpolated from fire-scar data and the NPS Fire Atlas. Relatively few fire history studies to date have used fire-scar data to quantify spatially explicit patterns of surface fire frequency (but see Everett et al. 2000, Niklasson and Granström 2000, Heyerdahl et al. 2001, Taylor and Skinner 2003, Jordan et al. 2005, Iniguez et al. 2008). The results of this study suggest that spatially explicit inferences from distributed fire-scar data may be more robust than recognized previously (Hessl et al. 2007). Unlike high-severity fires that create distinct evidence of fire perimeters in tree or shrub size/age structures (Johnson and Gutsell 1994, Turner and Romme 1994, Minnich et al. 2000), discrete boundaries of low-intensity surface fires are generally not discernible more than a few years after burning (a pattern we observed in the field repeatedly). Spatial patterns of low-intensity surface fires may be impossible to reconstruct to annual resolution from aerial photos in contemporary landscapes, because overlapping burns or adjacent short-interval burns often occur between aerial photo flights (Stephens et al. 2003). There were six major overlapping surface fires on Mica Mountain between available aerial photo sets that would have been missed using repeat aerial photo interpretation methods employed by Minnich et al. (2000). Given these considerations, we suggest that fire-scar data not only are useful, but are necessary to accurately characterize long-term spatial variation in frequent surface fire regimes.

We attribute the high corroboration between interpolated fire-scar maps and NPS Fire Atlas maps in this study to several factors. First, our sampling network was well distributed spatially, which improved the accuracy and precision of interpolated fire boundaries between burned and unburned plots (see Van Horne and Fulé 2006, Farris 2009 for a comprehensive empirical analysis of the effects of different spatial sampling strategies). Second, plot-level compositing reduced Type II error, which increased the quality (completeness) of interpolation data points. Third, the high quality of the NPS Fire Atlas reduced potential mismatches between the data sets that may result from mapping errors in the "reference" data (Shapiro-Miller et al. 2007). The Saguaro National Park fire atlas may be relatively unique compared to many other atlases in terms of the long temporal consistency and high accuracy and completeness of intensive mapping efforts. Finally, there was a well-defined area of inference (study area boundary) that provided a clear interpolation border to reduce potential edge effects.

We found a much stronger correlation between interpolated fire-scar perimeters and mapped fires in our study than Collins and Stephens (2007), who reported that fire-scar data generally underestimated fire extent and area in their study area. This was likely because they used a more conservative interpolation procedure (convex hulls assume no fire spread beyond the outermost points), their fire-scar data were less densely and evenly distributed, and consisted of individual tree sample units (many of their samples were based on stratification of mapped burn frequency), and possibly because of differences in the fire atlas quality (particularly for older fires), which is typical across multiple management units (Morgan et al. 2001, Shapiro-Miller et al. 2007).

A broad distribution of fire-scar samples (assuming they are present) combined with relatively simple nearest neighbor assumptions and interpolation rules such as Thiessen polygons appear robust for reconstructing complex spatial burn patterns of fire frequency. The demonstrated efficacy of this fire perimeter interpolation approach is a reflection of strong spatial autocorrelation inherent in fire spread and the resultant formation of synchronous fire scars. More complex geostatistical procedures are available for interpolating point-based fire-scar data and may produce smoother surfaces (e.g., Jordan et al. 2005, Hessl et al. 2007), but they have not been tested empirically against independent reference data, and it is unknown whether they result in a significant increase in accuracy, particularly given the relatively coarse resolution of most fire perimeter interpolations. Moreover, most linear interpolation methods for binary data can be expected to perform similarly when sample size is high and/or area burned is dominated by relatively widespread fires (Burrough and McDonnel 1998).

Any spatial interpolation from point data is subject to a minimum interpretable mapping resolution, below which the actual spatial pattern is unknown or indistinguishable from noise or error. This resolution is largely a function of sample density and quality (i.e., completeness or reliability of the fire record at each data point). One useful measure of resolution is the minimum mapping unit (MMU), defined as the smallest map element that can be reasonably detected (Quattrochi and Goodchild 1997). A minimum estimate of the MMU for interpolated fire-scar maps in this study area would be twice the average density of samples, because at least two adjacent plots were required to determine if a fire spread between them. Given an average sample density of 1 plot per 46 ha on Mica Mountain during the study period, a conservative estimate of interpolation MMU might therefore be $\sim$92 ha (on average). As we have shown, this resolution is sufficient to detect distinct spatial patterns of fire frequency in our study area, and is adequate to address most landscape-scale research and management applications.

It should be noted also that issues of resolution, data quality, and uncertainty are inherent in all fire history data sets, including fire atlas maps (Morgan et al. 2001, Shapiro-Miller et al. 2007). Recent remote sensing approaches eventually may increase the spatial and attribute resolution of mapped fire history data, but obviously only for contemporary fire events where instrument measurements are available (Key and Benson 2002, Miller and Thode 2007).

Fire frequency statistics: "accuracy" and implications

Given the strong spatial and temporal corroboration between fire scars and mapped fire perimeters in our study, it is not surprising that fire frequency summary statistics were so similar between the two data sources. Compared to the NPS Fire Atlas, the fire-scar NFR differed by $<$3 yr, and the fire-scar MFI estimates differed by 0 to 4 yr depending on the level of filtering and methodology. This difference is not large enough to substantially affect ecological interpretations or management implications in the study area. These results show that fire-scar sampling networks can accurately represent a wide range of metrics to summarize distinctly different aspects of the fire frequency–area distribution.

Our results illustrate also how the value and interpretation of different fire frequency statistics can differ for the same set of known fire events. This has important implications because much of the debate and confusion about fire-scar-based fire histories can be traced to incongruent statistical comparisons and interpretations of different summary statistics. It has been argued, for example, that fire-scar fire histories are "biased" because they give undue importance to small fires that are frequent but burn little cumulative area, but those conclusions have been based largely on inappropriate comparisons between the unfiltered composite MFI_{all} and NFR (see Minnich et al. 2000, Baker and Ehle 2001, 2003, Kou and Baker 2006). The MFI_{all}, however is not designed to measure cumulative area burned like the NFR. Given the clear and contrasting definition of the two metrics (Romme 1980), we submit that differences between them do not demonstrate a fire-scar bias but an interpretation error (Fulé et al. 2003, Stephens et al. 2003, Parsons et al. 2007). The results of our empirical corroboration demonstrate clearly that (a) fire-scar data can produce accurate estimates of NFR and large-fire frequency when that is the objective, and (b) statistical influence of small fires on interval estimation can be effectively eliminated through filtering. Other empirical comparisons between fire-scar data and fire atlas maps have demonstrated in fact that fire-scar data often *underestimate* large fire extent and cumulative area burned (and resultant NFR calculation) due to unrecorded fires (see also Collins and Stephens 2007, Shapiro-Miller et al. 2007).

The relationship between the MFI and NFR can be complex (Stephens et al. 2003, Kou and Baker 2006, Van Horne and Fulé 2006, Collins and Stephens 2007, Farris 2009), and neither measure is appropriate for all circumstances or objectives. Attempts to equate or convert directly between them may potentially lead to misleading conclusions about fire occurrence and management implications rather than clarification. For example, Baker and Ehle (2001, 2003) proposed correction factors to "convert" published values of the MFI_{all} closer to what they believed true NFRs for those stands might be (although empirical values were unknown). Based on that analysis they suggested presettlement NFRs in western ponderosa pine forests ranged from a median of 52 yr at the low end to 170 yr at the high end (overall range 22–308 yr), and that prescribed burning at intervals shorter than 20 yr lacked sound scientific basis (Baker and Ehle 2003). Our empirical corroboration does not support those conclusions. Even the 20th century, fire suppression era NFR of 27 yr on Mica Mountain falls at the lowest range of "corrected" presettlement (pre-1900) era values proposed by Baker and Ehle (2001). Applying the same methodologies tested successfully in this study, Farris (2009) calculated a presettlement NFR of 9–11 yr on Mica Mountain and two other study sites in the Southwest, which are less than half the value of the lowest "corrected" value by Baker and Ehle (2001) (and five times lower than the estimated lower median). These values not surprisingly are consistent with large fire intervals (i.e., $\geq$25% filter level) reported throughout the region: the median $MFI_{25\%}$ for 63 ponderosa pine and pine-dominated mixed-conifer forests in the Southwest (including Mexico) was 12.7 yr (Swetnam and Baisan 1996*b*). Fires of this size are accurately and completely inventoried with fire-scar data and have the strongest influence on the NFR (see also Stephens et al. 2003, Van Horne and Fulé 2006, Collins and Stephens 2007). Moreover, Van Horne and Fulé (2006) and Farris (2009) found little difference between systematic, random or targeted presettlement interval estimates of widespread fire (>25%) intervals in northern Arizona ponderosa pine. We conclude that direct conversions between different fire history statistics conflate their interpretation and may lead to erroneous conclusions (Stephens et al. 2003). A more prudent approach would be to reanalyze original data (if possible) or to restrict new inferences in a manner consistent with the limitations of the existing and intended definitions of fire history statistics (Romme 1980).

It was not our intent to argue that any single summary statistic (e.g., MFI or NFR) is best for all scales or applications. All summary statistics have advantages and disadvantages depending on the research objectives, available data, scale of analysis, and aspect of the fire frequency–area distribution one wishes to emphasize. Our purpose instead was to assess the relative "accuracy" of individual metrics reconstructed from fire scars by way of empirical corroboration with independently mapped fire perimeters. Given the strong empirical agreement between fire-scar data and mapped fires, we agree with Fulé et al. (2003) and Veblen (2003) that multiple statistics should be presented to provide the most complete picture and interpretation of fire occurrence at multiple scales and resolutions within a study area. In our study area, for example, one could determine from the various statistics in Table 4 that an area equivalent to the study area was burned approximately every 27 yr on average. Fires that burned at least 10% of the sampled plots or study area occurred every 6.7–9.2 yr on average, respectively, and fires that burned at least 25% of the plots or study area occurred every 25.5 yr. Although a fire occurred somewhere in the study area every year, the number of fires occurring within individual 1-ha sampling plots during the 64-yr study period ranged from 0 to 9. When examined in tandem with mapped representations (Fig. 6), distinctive spatial patterns of multi-decadal fire frequency become evident, such as highest fire frequencies at the summit of Mica Mountain, and lower frequencies at lower elevations (similar patterns can be detected from simpler analyses of scarred sample locations and/or master fire chronology charts). Examining multiple statistics in tandem should lead to a clearer and more traceable interpretation of fire frequency characteristics, including analytical assumptions and uncertainties.

Fire seasonality

Interest in using fire-scar data to determine fire seasonality has increased in recent years as more research has focused on regional fire-climate variation and long-term influences of climate change on fire occurrence (Grissino-Mayer and Swetnam 2000, Grissino-Mayer et al. 2004, Swetnam and Anderson 2008). Our empirical results reaffirm the strong relationship between intra-annual ring position of fire scars and seasonal fire occurrence in the Southwest. Fulé et al. (2003) found a similarly strong agreement between documentary fire years and empirical fire-scar ring positions in northern Arizona. Together, these studies demonstrate that long-term analyses of fire seasonality have an accurate basis in tree physiology. It should be noted, however, that the cambial phenology of ponderosa pine and a few other tree species has been relatively well studied in the Southwest (e.g., Fritts et al. 1976, Baisan and Swetnam 1994; C. D. Allen, *unpublished data*). Such detailed phenology data may be lacking in other regions and tree species. Given the increasing interest in broadscale geographic variation in seasonal fire occurrence, similar comparisons between tree growth and intra-annual scar positions in other regions would be very useful.

Additional considerations

This study provided a rare opportunity to compare fire-scar data with independent, annually resolved fire maps in a frequently burned landscape. The Saguaro National Park fire atlas contains a relatively detailed and consistent record for the 64-yr study period, but it can not be considered to be the unconditional "truth." All data types of significant temporal length and spatial coverage available to us contain varying levels of resolution and uncertainty. Hence, in some ways the comparison of fire-scar data with historical mapped fire perimeter data is also a test of the accuracy and precision of the fire atlas data. The strength of the spatial and temporal corroboration between fire-scar data and the NPS Fire Atlas suggests that both data sets are relatively accurate representations of the 20th century fire history at the resolution and scale analyzed.

This research represents a single case study in one forest type, a circumstance that is true of all site-specific fire history research, and a great many other ecological studies. However, the climate, topography, forest, and fire environment on Mica Mountain is qualitatively similar to many "sky island" pine forests throughout the Southwest borderlands. The similarity of presettlement ponderosa and mixed conifer fire regimes in these mountain ranges is supported by the broad similarity in fire history statistics (i.e., MFIs, filtered and unfiltered) from >30 sites of similar size and forest type in this region (Baisan and Swetnam 1990, Swetnam 2005, Iniguez et al. 2008).

Finally, from a fire history perspective we conclude the 20th century fire regime on Mica Mountain provides an especially rigorous test bed for testing the accuracy of fire-scar-based estimates of fire frequency and spatial fire pattern. Our data set indicates that prior to 1900 large fires were considerably more frequent and extensive than during the test period. The largest fire during the 20th century, for example, would have been only the ninth largest fire reconstructed during the 19th century (Farris 2009). There is also strong evidence of more spatial clustering and variability in fire frequency during the 20th century than the 19th century, as evidenced by the fact that some areas burned nine times and others not at all. Had documentary fire maps of the typically larger 19th century fires been available for comparison, we believe that corroboration with the fire-scar record would be even stronger and more robust, because widespread fires are inventoried more completely and accurately. We conclude that the analytical methods tested in this study are very appropriate for reconstructing historical fire occurrence during the presettlement era.

Acknowledgments

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